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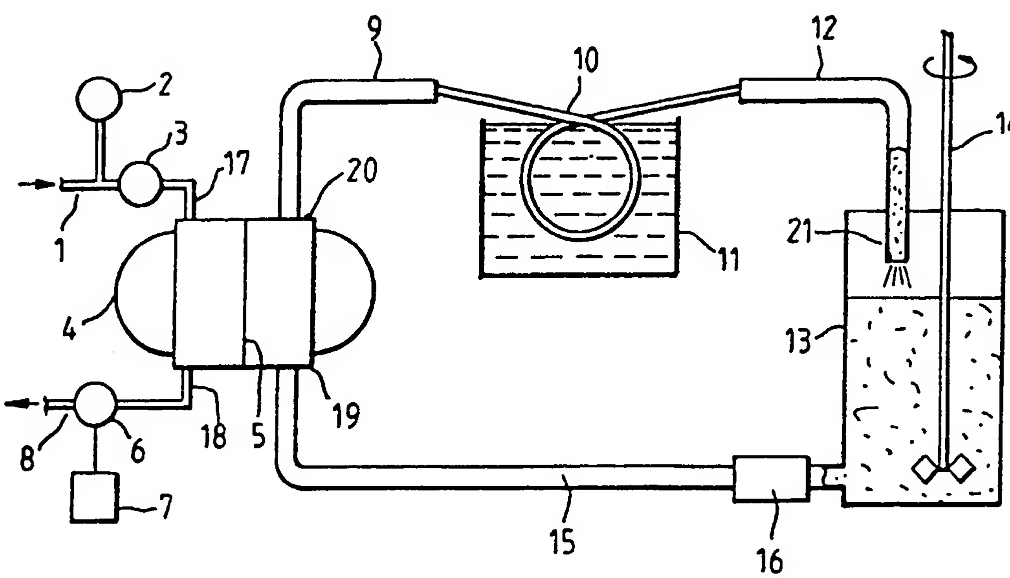
(54) **Pipe rheometer**

(57) A pipe rheometer comprises a fluid-operated diaphragm pump 4 having a pump input 19 and a pump output 20, the pump input receiving the liquid substance e.g. drilling fluid and the pump output being connected to one end of the pipe 10, the other end being at atmospheric pressure, a gauge 2 for measuring the pressure of said fluid e.g air operating the pump and means 6 for measuring the flowrate of the liquid substance circulating in the pipe. The operating fluid, air, is supplied via gauge 2 and oiler 3 to the pump 4 and is exhausted via outlet 18, pneumatic switch 6 and electronic timer 7 and line 8. The pneumatic switch 6 and timer 7 count the number of pump strokes/unit time to give the flow rate measurement. The diaphragm 5 separating the liquid substance from the pump operating fluid ensures that their pressures are substantially equal. A mixer 14 in reservoir 13, which may be the mud pit or the mud return channel for the drilling mud of an oilfield or the like, agitates the liquid substance and a motionless inline mixer 16 in line 15 returning the substance to pump input 19 homogenises the fluid substance.

Fig.1



At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

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Fig.1

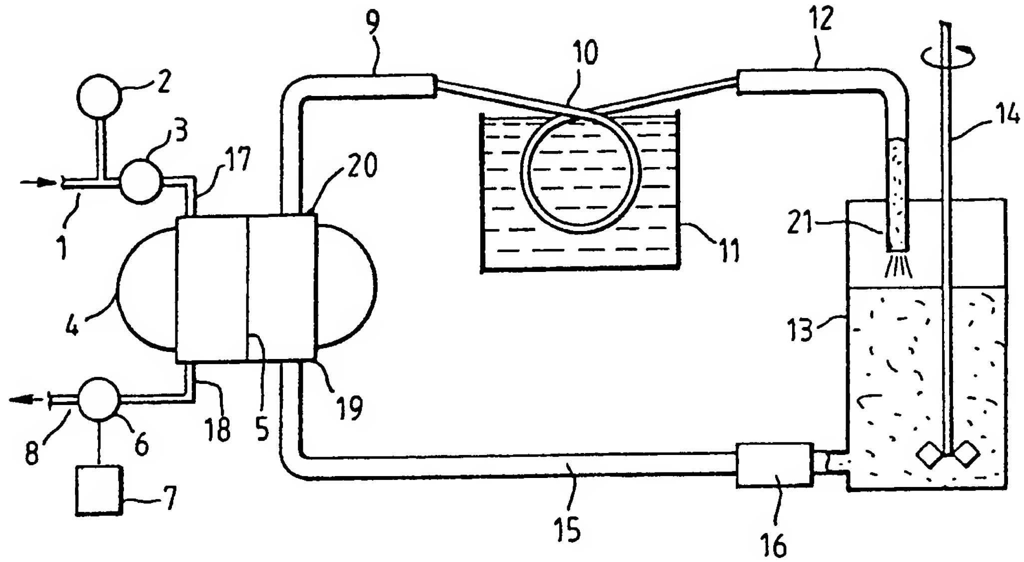

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Fig.2

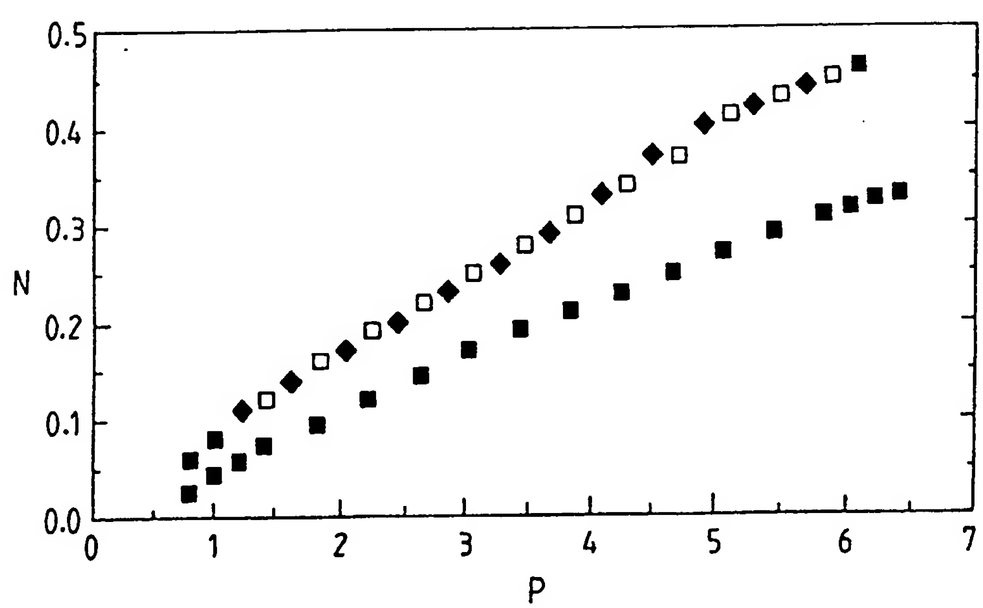

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Fig.3

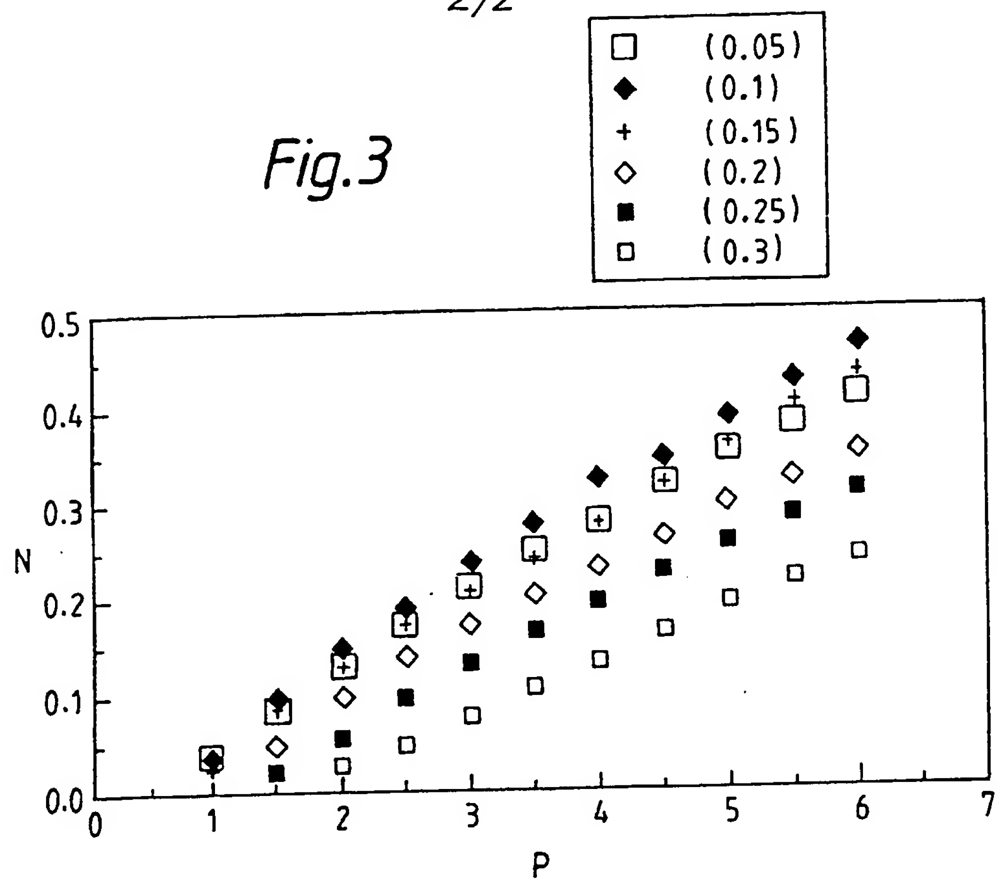
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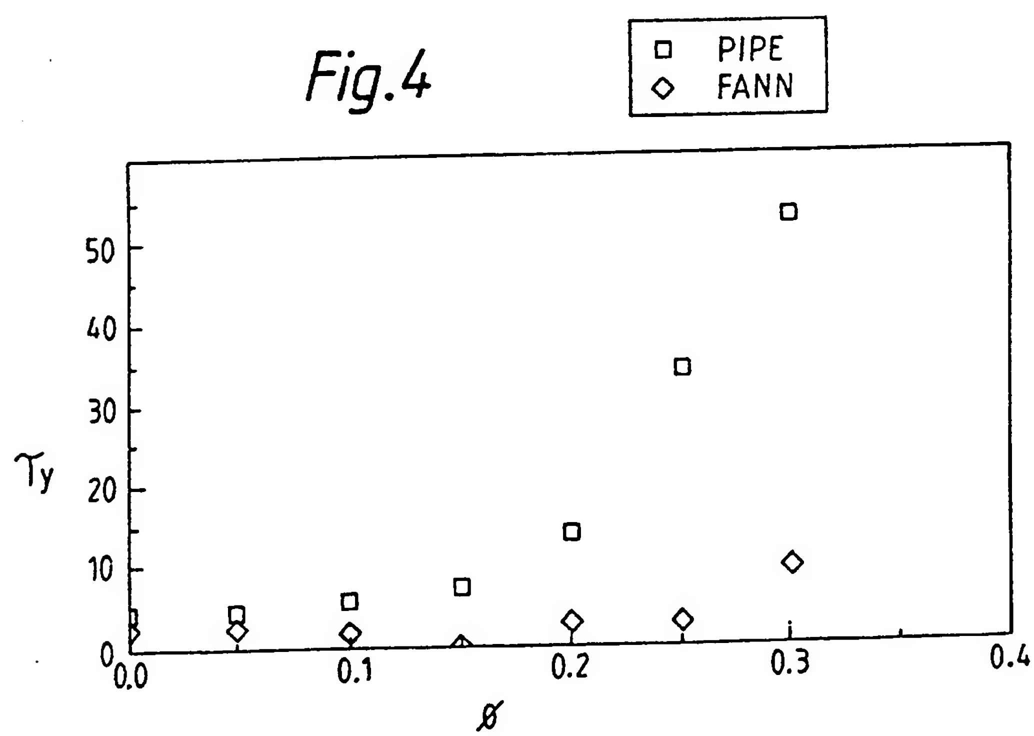
Fig.4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PIPE RHEOMETER

The present invention relates to a pipe rheometer to measure the rheological properties of a liquid substance, mainly its viscosity and yield stress. The invention is particularly suitable for measuring the rheological properties of the liquids in use, such as the drilling fluids used when drilling oil, gas or geothermal wells.

When drilling a well with a drillstring having a drill bit attached at its lower end, a liquid substance, known as "drilling mud", is circulated from a mud pit at the surface into the drillstring down through the drill bit and then upward in the annulus formed between the drillstring and the borehole back to the surface in the mud pit. The drilling mud has several purposes, among them to create a predetermined hydrostatic pressure in front of the formation being drilled and to lift the drilled cuttings from the drill bit area to the surface where they are separated from the mud. Additives are mixed with the mud at the surface to obtain the characteristics of the drilling mud in accordance with predetermined specifications. It is therefore important to control the drilling mud characteristics, such as its rheological properties, during the drilling operations so as to keep them within the specifications by adding or withdrawing some additives.

Other wellbore fluids are used, such as cements, spacers and completion fluids, for which the rheological properties must be controlled and adjusted if necessary.

Current techniques set by the American Petroleum Institute (API) to measure the rheological properties of the various wellbore fluids are based on the time taken for a sample to empty from a funnel of specified geometry ("Marsh funnel") or on the torque transmitted between two concentric and coaxial cylinders when one of them is rotated ("Fann rheometer" or its equivalent).

The Marsh funnel method is comparative only and does not give the shear stress-shear rate ($\tau(\gamma)$) relationship required for calculation or modelling of downhole flows. The Fann rheometer, which is the most commonly used in the oil industry, can give in principle the required relationship $\tau(\gamma)$ but in practice is subject to many sources of error and disturbances to its expected mode of operation.

Pipe rheometers are used currently in the laboratory where the environment in not harsh.

The physical principles governing the operation of the pipe rheometer are well-known. The rheology of the liquid is obtained from the laminar frictional pressure drop P across the ends of a pipe of known geometry for a volumetric flux Q. If P(Q) is the measured function, the relationship $\tau(\gamma)$ can be derived from it by suitable treatment of the data, as explained later on.

Comparisons between the Fann and other types of rheometer have shown the Fann rheometer to be good for measuring the rheological properties of Newtonian or non-Newtonian liquids. Problems occur when measuring the rheological properties of non-Newtonian liquids containing large or dense particulate materials. Most wellbore fluids used in petroleum engineering are in this category, eg drilling muds, cements and spacers.

Pipe rheometers have several advantages compared with the Fann rheometer. For example, the Fann rheometer is essentially a discrete sampler, requiring subtraction of liquid from a point in the process and delivery to the point of measurement. By comparison, pipe rheometer is intrinsically recurrent and in operation can be arranged to continuously subtract liquid, measure its rheological properties, and return the liquid to the process stream.

In addition, there is no effective means in the Fann rheometer for the resuspension of heavy particles. Progressive sedimentation out of the sensing region between the cylinders during the measurement gives time-dependent and erroneous results. In the pipe rheometer, where the liquid in the pipe is being continually replenished, there is no time-dependent sedimentation.

Furthermore, centrifugal migration of the heavy particles in the Fann rheometer causes inhomogeneous rheological properties of the liquid within the sensing zone, leading to time-dependent and erroneous results. These can be eliminated in the pipe rheometer by the proper design and conformation of the pipe.

Also, most wellbore fluids are thixotropic liquids, ie their rheological properties at a given time depend on the flow history of the sample prior to that time. Thus the rheological properties of the drilling fluids circulating in the wellbore are in general different following a period of rest. The continuous circulation of sample in the pipe rheometer more closely resembles the continuous circulation of wellbore fluids than the discrete sampling of the Fann rheometer.

In spite of its advantages over the Fann rheometer, the pipe rheometer is almost never used at the drilling site because it is a rather delicate instrument which is difficult to use in the harsh environment of a drilling rig. For example, the pipe rheometers of the prior art usually comprise strain gauges to measure the pressure drop of the liquid circulating in the pipe and a flowmeter to measure the flowrate of the liquid in the pipe. Measurements, made directly in the drilling fluids, are difficult because of the complicated structure of these liquids.

The present invention provides a pipe rheometer which is robust enough to be used in a rough environment. It does not require any pressure measurements to be made in the liquid substance whose rheological properties are to be determined.

More precisely, the present invention relates to a pipe rheometer for measuring the rheological properties of a liquid substance, of the type having a pipe in which said substance is circulated, the pipe rheometer comprising a fluid-operated diaphragm pump having a fluid-inlet line, a fluid-outlet line, a pump input and a pump output, the pump input receiving the liquid substance and the pump output being connected to one end of the pipe, the other end being at a known pressure, a gauge for measuring the pressure of said fluid operating the pump and means for measuring the flowrate of the liquid substance circulating in the pipe.

The known pressure is advantageously the atmospheric pressure and the means for measuring the flowrate of the liquid substance comprises means for counting the number of pump cycles during a certain period of time.

A specific embodiment of the invention will now be described by way of non-limiting example only, with reference to the accompanying drawings, wherein:

- Figure 1 is a schematic diagram of a pipe rheometer in accordance with the present invention;
- Figure 2 represents the number N of pump strokes per second versus different air pressures P, for two glycerol-water mixtures of different viscosities;
- Figure 3 represents the number N of pump strokes per second versus different air pressures P, for a waterbase drilling mud weighted with barite at different volume fractions; and
- Figure 4 shows a comparison of the yield stress data versus different concentrations of barite in a waterbase drilling mud, obtained with a pipe rheometer and a Fann rheometer.

Figure 1 shows a schematic diagram of the pipe rheometer in accordance with the present invention. Compressed air is supplied via line 1 and the air pressure P relative to atmospheric pressure is set and read by the regulator gauge 2. Oiler 3 passes compressed air to a diaphragm pump 4 via a fluid-inlet line 17. The purpose of the oiler 3 is to lubricate the pump by delivering a fine spray of oil. The pump exhausts the air at a pressure very close to the atmospheric pressure via the fluid-outlet line 18, pressure switch 6, electronic timer 7 and line 8. The pressure switch 6 counts the number N of pump strokes during a time unit (one minute, for example). The pump 4 is a fluid-operated diaphragm pump, the fluid being preferentially air. The pump has an input 19 and an output 20. The pump works on a well-known principle whereby there are two chambers which communicate with the liquid substance where rheological properties are to be measured and wherein the liquid substance and the air are separated by a flexible membrane of rubber or of similar material indicated schematically by the reference 5 in Figure 1. By a combination within the pump of pneumatic switching for

the air and one-way valves for the liquid substance, the supply of compressed air alternatively sweeps the liquid substance out of each chamber, around the liquid substance circuit 9, 10, 12, 13 and 15 and back to the pump. The pump can be for example the $^1/_2$ inch (or 1.27 cm) diaphragm pump manufactured by The ARO Corporation, Ohio, USA. Large-diameter line 9 connects the pump output 20 to the pipe 10 which may be cooled by a suitable water bath 11 or by convection to ambient air if the temperature rises are small. Water bath 11 may also be heated or cooled away from ambient temperature if rheology-temperature characteristics of the liquid substance are required. Pipe 10 will be generally of smaller internal diameter and longer than the other pipes 9 and 12 in the liquid circuit. This ensures that the sum of the friction pressures developed across the other pipes is negligible compared with that across pipe 10 in which the rheological properties are to be measured and for which the length and internal diameter need to be know. In the described embodiment, the internal diameters of pipes 9-12 and of pipe 10 were 12.7 mm and 4 mm respectively. The length of pipes 9-12 could be between 0 and 1 meter and the length of pipe 10 could be between 3 meters (for thick liquid substance) and 30 meters.

Pipe 12 leads the liquid substance to vessel 13. The end 21 of pipe 12 is at atmospheric pressure and is located above the level of the liquid substance in vessel 13. In the laboratory, vessel 13 would be any suitable container large enough to contain several chamber volumes of the pump, preferably agitated by mechanical stirrer 14 to ensure mixing and continued suspension of any high-gravity solids. For continuous measurement of rheological properties of the drilling mud in oilfield or similar applications, vessel 13 represents the mud pit, or one of them when several are used, or more generally the open mud return channel. Line 15 returns the liquid substance to pump input 19 from near the bottom of vessel 13, hence maximising the pick-up of high-gravity solids. To homogenise the fluid, an in-line motionless mixer 16 (for example, the one manufactured by the company Koflo) is incorporated in return line 15. The time taken to empty each chamber of the pump is determined as the time period T between consecutive pressure pulses originating from the pneumatic switch mechanism of the pump. Each pressure pulse is detected by the pressure switch 6 which passes an electrical pulse to activate the electronic timer 7. The pump characteristics being known, more especially the volume of each chamber, the volume flowrate of the liquid substance is easily obtained form the time period T, or the pump frequency N which is equal to $^1/_T$.

As indicated, the liquid substance and the air are separated in the pump by the flexible membrane 5. As a result, the pressure P of the air measured with the gauge 2 is substantially equal to the pressure of the liquid substance in the pump, except for a small pressure difference which could be neglected. Calibration tests have shown that

this small difference was equal to 0.35 bar for an air pressure P of 7 bars. However, by calibrating the pump, this small difference in air pressure and liquid substance pressure in the pump can be taken into account.

In accordance with the present invention, the pressure drop in the pipe 10 (the pressure drop in pipe 9 and 12 being negligible) is taken equal to the pressure at the pump output 20 (which is equal to the air pressure P) provided pipe output 21 is at the atmospheric pressure. The small pressure difference above mentioned can be taken into account, if wanted, after calibration of the pump. The pressure at the end 21 of pipe 12 is supposed to be known, if not at atmospheric pressure. The pipe rheometer does not require any pressure measurement to be made in the liquid substance; these are made only in the compressed air. A separate flowmeter is also not necessary since the volume flowrate is obtained from the pump characteristics.

On the theoretical point of view, the yield stress τ_y and the plastic viscosity η of the liquid substance are determined from the following equations. For a Bingham plastic liquid, which is given as an example, the shear stress τ is related to the shear rate γ by

$$\tau = \tau_y + \eta_B \gamma \qquad (1)$$

where τ_y is the yield stress and η_B is the Bingham plastic viscosity. This is the relation usually assumed for drilling muds and cements.

For Bingham liquid flow in pipe of interior radius a and length l the Buckingham equation (Govier and Aziz, 1972, p 196, *The Flow of Complex Mixtures in Pipes*, Krieger, Florida, USA) relates the volume flow rate Q to the pressure drop P across the pipe ends by

$$Q = \frac{\pi a^4 P}{8 l \eta_B} \left(1 - \frac{4}{3} \left(\frac{\tau_y}{\tau} \right) + \frac{1}{3} \left(\frac{\tau_y}{\tau} \right)^4 \right) \qquad (2)$$

where τ is the shear stress at the pipe wall. For $\tau >> \tau_y$ the τ^4 term can be ignored. Using $2l\tau = aP$ and putting $Q = NV_c$ wherein V_c is the volume per stroke of the pump and N is the pump frequency ($N = 1/T$), the following equation is obtained:

$$N = \frac{\pi a^4}{8 l \eta_B V_c} P - \frac{\pi a^3 \tau_y}{3 \eta_B V_c} \qquad (3)$$

which shows that a graph of N plotted with P has a slope inversely proportional to the plastic viscosity η_B and an intercept proportional to the ratio τ_y/η_B of the yield stress over the plastic viscosity.

For non-Bingham fluids, such as Newtonian or "power law" liquids, equations (1) to (3) are different, but well-known. They can for example be found in the above-mentioned reference. However, the method of measuring the viscosity and the yield stress from N and P remains valid.

In use, the chamber-emptying time T is measured for different air pressures P. For any Newtonian liquid, the pump frequency N plotted with P should be linear with a zero intercept. Figure 2 shows such a plot for two Newtonian glycerol-water mixtures of two different viscosities (the larger viscosity corresponding to the lower curve), showing deviations from linearity at low pressures, but with the bulk of the data obeying the expected linearity. N is expressed in second^{-1} and P in bar. The deviations from linearity at low pressures are attributable to mechanical friction or other imperfections of the pump. Deviations from linearity at high pressures are attributable to the onset of turbulence. The viscosity of the liquid is obtained from the slope of Figure 2 in the linear region and good agreement was found with the viscosity measured directly using a Fann rheometer.

Figure 3 shows also the frequency pump N versus different air pressure P, but for a weighted waterbase drilling mud, a Bingham liquid, with six different volume fraction, from 0.05 to 0.3. The deviations from linearity at low and high pressures remain and exist for the same reasons as for the Newtonian liquid, ie as in Figure 2. A new feature is the non-zero intercept on the P axis which, in accordance with equation (3), leads to the yield stress τ_y of the mud. The slopes of the linear portions of Figure 3 also give the plastic viscosity of the mud.

Figure 4 shows a comparison of the yield stress τ_y measured for different volume fractions ϕ of the mud-weighting agent barite using both the 6-speed Fann rheometer and the pipe rheometer. Whereas the Fann data shows decreases in yield stress with increasing barite volume fraction ϕ (which is believed to be erroneous), the pipe rheometer shows that τ_y increases with ϕ, as expected on any reasonable physical grounds.

The rheometer of the present invention, which can be used either as a laboratory instrument or kept running to continuously interrogate mud rheology during drilling, is driven by compressed air which is intrinsically safe in hazardous environments. Also, by maintaining a continuous circulation of the mud, the measured rheology is close to that which is defined by similar continuous circulation conditions in the wellbore. In addition, the rheometer overcomes sedimentation of particles, eg by mixing in the pump, by a stirrer or by mixing sections in the flow line, and rheologies of fluids having particles up to about 2 mm in size can be measured.

Claims:

1 A pipe rheometer for measuring the rheological properties of a liquid substance, of the type having a pipe in which said substance is circulated, characterized by further comprising a fluid-operated diaphragm pump having a fluid-inlet line, a fluid-outlet line, a pump input and a pump output, the pump input receiving the liquid substance and the pump output being connected to one end of the pipe, the other end being at a known pressure, a gauge for measuring the pressure of said fluid operating the pump and means for measuring the flowrate of the liquid substance circulating in the pipe.

2 The pipe rheometer of claim 1, wherein said known pressure is the atmospheric pressure.

3 The pipe rheometer of claim 1 or 2, further comprising a thermostatic bath in which at least part of the pipe is enclosed so as to keep the fluid in the pipe within a predetermined range of temperature.

4 The pipe rheometer of one of the claims 1 to 3, wherein the means for measuring the flowrate of the liquid substance comprises means for counting the number of pump cycles during a certain period of time.

5 The pipe rheometer of claim 4, wherein the counting means are a pressure switch located in the fluid-outlet line and a timer connected to the pressure switch.

6 The pipe rheometer of any of the preceding claims, wherein the pressure gauge is in the fluid-inlet line.

7 The pipe rheometer of any of the preceding claims, further comprising fluid pressure-regulation means in the fluid-inlet line.

8 The pipe rheometer of any of the preceding claims, wherein the liquid substance is contained in a tank and the other end of said pipe is located above the surface of the liquid substance in the tank, further comprising a return line connecting the tank with the pump input.

9 The pipe rheometer of claim 9, further comprising a mixer in the return line.

10 The pipe rheometer of claim 8 or 9, further comprising a stirrer in the tank.

11 The pipe rheometer of any of the preceding claims, further comprising a first connecting line interjoined between the pump output and said one end of the pipe and/or a second connecting line fixed at said other end of the pipe, the geometry of said connecting lines being such that the pressure drop of the liquid substance circulating in there is small compared with the pressure drop of the liquid substance circulating in the pipe.

12 The pipe rheometer of any of the preceding claims, wherein the pressure gauge is calibrated so as to account for the slight difference between the pressure measured in the fluid-inlet line and the pressure of the liquid substance at the pump output.

13 The pipe rheometer of any of the preceding claims, wherein the fluid is compressed air.

14 Application of the pipe rheometer of any of the preceding claims to the measurement of the rheological properties of a drilling fluid by measuring the fluid pressure P and the pump frequency N.

15 The application of claim 14, using the rheometer of claim 8, 9 or 10, wherein the tank is one of the pits containing the drilling fluid of a drilling rig.

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